A GIS-CA model for planning bikeways upon the footpath network

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Abstract: This study proposes a Geographic Information System (GIS)-based cellular automata (CA) model, which is designed for planning bikeways upon existing footpath network within an urban area. The CA model was developed based on a GIS platform as a visual interface whereby spatiotemporal characteristics and spatial processing can be combined in a highly effective way. The host value of each CA cell was conditioned upon four indicator variables, namely cycling demand level, land use nature, social value, and traffic safety. This model gives traffic planners a quick and intuitive framework to develop cycling facilities under limited land resources. A model prototype has been developed in a common desktop GIS and applied to a mid-sized rapidly developing area in Singapore.

Key words: bikeway network planning, bike-sharing scheme, Geographic Information System, cellular automata model

1 Introduction

Cycling is one of the main transport modes in an urban transportation system and is being rapidly revitalised for its sustainability and green life-style. Singapore, as well as other big cities, is striving to promote extensive cycling usage in urban areas. The long-term aim is to provide all 26 towns with a comprehensive cycling network. Within confined land area, provision of cycling facility and bike-sharing scheme shall be an effective way to enhance first-/last-mile connectivity, which has become very popular and advanced in some European countries [1-3]. On the basis of cycling demand forecast, the network of docking stations upon the footpath network can be determined. Cycling has been a minor mobility mode in Singapore over the 80's and 90's, hence there is hardly extant on-road cycling lane or off-road bikeways. Given the apparent risk faced by cyclists on the narrow urban roadways in Singapore, utilitarian cyclists have, by and large, come onto the footpaths (typically 1.5m wide pathways) which generates conflicts with the pedestrians. Singapore passed the Active Mobility Bill in 2017 which accords cyclists the right to jointly use off-road footpaths amidst pedestrians, with a 15km/h speed limit [4], which was subsequently amended to 10km/h [5]. Where demand is high, the footpaths have been widened for shared-use by pedestrians and cyclists [6]. Furthermore, docking stations are located along the bikeway network as bike-sharing nodes. How to plan a conjoint walking and cycling facility is an important issue in implementing Singapore's bike-sharing scheme in order to satisfy the cycling demand without excessive uptake of new land space. Some amount of research work has been done in the cycling field in recent years. For instance, cycle route network planning was highlighted in recent years in order to develop multi-modal sustainable transportation systems [7]. Yet, there exists little research on how to plan a new bikeway network layered upon existing footpath network.

This study fills the gaps of research findings by presenting the development of bikeway network on existing footpaths using a Geographic Information System (GIS)-based cellular automata (CA) model. The model captures four main factors that influence the prioritisation and location of bikeways juxtaposed onto existing footways. The key factors are land use nature, cycling demand level, traffic safety, and construction difficulty. The model provides the flexibility to collate relevant data into an easily interpretable graphical format, which has strong practicability. Moreover, with the application of a GIS platform, the results can be shown directly. The selection of off-road bikeways is the most important topic being considered, aimed at providing the maximum benefit for both cyclists and the authorities [8].

The proposed planning framework is well suited for planning a bikeway network for cities with sparse cycling infrastructure yet cycling and bike-sharing is rapidly growing in demand. The findings are clean-cut and intuitive, which can be effectively used to plan cycling facilities within confined land area. The proposed model may not be the most accurate tool for planning every kind of bikeways but can be improved as data for various factors are built up. Moreover, the attribute values shall be adjustable as commensurate with actual conditions.

Section two of the paper reviews the literature on planning cycling facility, and methods used in planning bikeways. The third section introduces the CA modelling theory and the applicability of CA and GIS combination for planning bikeway network. Section four describes and explains the proposed methodology used for planning bikeways. The fifth section applies the method in a district in Singapore. The final section provides the conclusions as well as the identification of opportunities for future research in this field.

2 Literature Review

Cycling facility planning model has drawn attention among transportation academic research area since the mid 1990s. The models generally fall into three groups: supply-based models, demand-based models and supply/demand-based models.

Supply-based models rely on two overarching theories: a) all major attractors should have cycling facility; b) a mathematical method, such as hazard score analysis, bicycle compatibility index (BCI), and level of service acceptability matrix (LOSAM) for cyclist and pedestrian, should be calculated to prioritise the cycling facility [6]. That is, cycling facility planning is either specialised or be improved based on the current condition of the level of service for cyclists. Bicycle compatibility index (BCI) is a typical supply-based model which is developed for U.S. metropolitan areas. A level of service acceptability matrix was proposed based on Singapore's local travel characteristics, which is easy and be quickly applied to assess current cycling situation and to propose necessary countermeasures. Although these supply-based models considered various important factors, such as traffic safety and interaction, there is still a lack of the foresight on the most "desired" path for cyclist.

Demand-based models focus on the cycling travel data from one zone to another. Therefore, this kind of models does not indicate site specific facility improvements or represent actual increase in usage if a cycling facility is implemented [9]. Demand-based models put a greater emphasis on cycling travel prediction including market analysis, facility demand potential models, discrete choice models, and aggregate behaviour studies. One of the most popular demand-based models is Latent Demand Score (LDS) model, which was proposed by [10]. This model estimates the probability of cycling travel on individual street segments based on their proximity, frequency, and magnitude of adjacent bicycle trip generators and/or attractors. However, LDS model may result in overestimation as it did not consider existing nearby high-LDS alternative routes.

Supply/demand-based model has been regarded as a reasonable method for cycling facility planning, as the balanced consideration for both supply and demand sides. Although this concept has been accepted by many scholars, there has been little research on how to combine both supply and demand sides to decide how to prioritise and plan the cycling facility [11, 12]. Recently, a data science framework was proposed which considers both potential demand and path prioritisation [13]. Their case study results showed that the data science framework can inform interventions and improvements to an urban cycling infrastructure. A heuristic and data-mining-based method was developed by [14] to weigh both Demand And/oR Equity (DARE) in the station distribution and allocation process of planning bike-sharing. DARE provides transparent decision-making support for supply distribution and presents an alternative where the benefits of bike-sharing system (BSS) are extended beyond privileged populations.

This study proposes a GIS-based CA bikeway planning method to address the gap in research into how to systematically plan a new cycling network layered upon an existing footpath or roadway network. CA bikeway planning model has been explored in detail by researchers in the past two decades with the aim to find an optimal path within minimum possible time. However, besides the incomplete consideration of influence factors, the traditional CA path planning method based on starting from part-to-whole approach suffers the shortcomings of easy to premature convergence. An improved CA bikeway planning method is developed using whole-to-part technique based on GIS platform. Path planning on GIS platform does not come out of the blue and has been successfully applied in other planning problems. As such, this paper adds CA model on a GIS platform to fill a gap in existing bikeway planning methods.

3 Cellular automata model

Cellular automata (CA) method was first proposed by [15] to simulate the self-reproducing function in a living system. [16] applied it widely by introducing system dynamics method, computer theory and formal language to CA research. CA is not determined by a strictly defined equation or formulation but is formed by a series of rules. Any model that satisfies these rules can be regarded as a CA model. A CA model usually includes five components: cell space, cell state, neighbour, transfer function and temporal state, as shown in Figure 1.

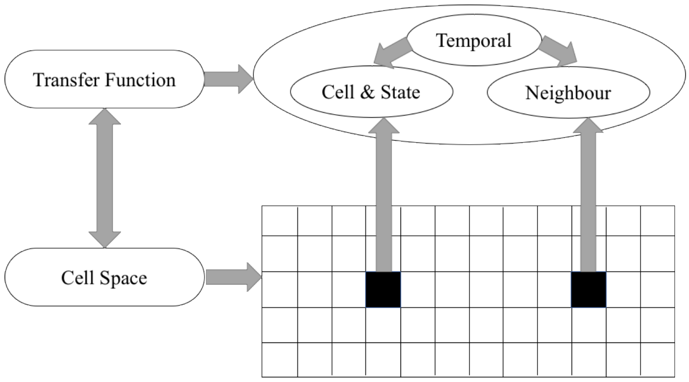


Figure 1 Components of CA

The applicability of CA model used in bikeway planning is on three aspects: (1) CA's bottom up modelling mechanism, starting from the state of the cell, can easily describe the behavioural regularity for determining the position of the cell, (2) the computational completeness of CA model is suitable for simulating the complex spatial cycling system, as CA has no defined set of formulation laws, and (3) CA model can be easily achieved by a computer program. CA model possesses the spatial and temporal characteristics that can describe bikeway's spatial distribution and changes in its development over time.

GIS-based technique has received more and more attention in recent decades as it can effectively manage, express, analyse and process static space information [17]. The advantages of using GIS in infrastructure planning have been widely discussed. It has also been applied in bikeway network planning in many countries, such as New Zealand, USA, Singapore, Greece [7, 18-20]. Both studies and practices have shown that GIS technique can well support the bikeway network planning decision making. However, it has so far failed to describe and simulate spatiotemporal behaviour in a geo-graphical framework. CA has a strong ability on simulating spatiotemporal behaviour, but the geospatial processing is relatively weak. Therefore, the combination of CA and GIS models can take full advantages of each other.

4 Method

4.1 Influence factor

A cell is set as a square with a side of length 30 metres. Each cell $c_{i,j}(x,y)$ has a host variable $w_{ij}(x,y)$ to determine the cell state, where (i, j) is the grid coordinate and (x, y) is the actual coordinate. A host variable is defined which has 3 kinds of value, including: "0" means the cell is not ideal for the planning path; "1" means the cell is a possible option; "2" means the cell is an ideal section along the planning path. The host variable is influenced by four indicator variables based on Singapore's conditions: land use nature x_1 ("0" means unavailable land, e.g. building, expressway, river etc. if x_1=0, then $w_{ij}(x,y)$=0, other variables will be unavailable to be valued; "1" means green space, which can be developed for widening adjoining footpath for shared-use; "2" means available space, which can be used for constructing shared-use pathway; "3" means existing footpath, which can be shared by cyclists); cycling demand level x_2 ("0" means low demand area with low priority, "1" means medium demand to be a shared-used pathway; "2" means high demand); traffic safety x_3 ("0" means a safe place; "1" means low hazard place; "2" means medium hazard place; "3" means high hazard place); construction difficulty x_4 which is related to the soil conditions, construction cost etc. ("0" means no difficulty; "1" means low difficulty; "2" means medium difficulty; "2" means high difficulty).

After generating the spatial distribution grid map, the data table can be organised based on the cells' attribute. According to the actual conditions, the required information for GIS platform includes hydrological feature, land use nature, and construction difficulty. After inputting these data into GIS, the corresponding grid map is generated onto the GIS platform with a corresponding data table. Each row represents a cell, which includes four fields: UserID (cell code), Pos (real location in geographic coordinate), Hos (host value), Ind (Indicator value).

4.2 Cell transfer rule

Based on the state of each cell in the planning area, the cell on the planning path shall be determined by three parameters: host value $w_{ij}(x,y)$, transfer rate parameters α, and transfer probability $P_{ij}(x,y)$.

a) Host value $w_{ij}(x,y)$

The host value can be calculated based on the four indicator variables as follows:

$$w_{ij}(x,y) = b_1x_1 + b_2x_2 - b_3x_3 - b_4x_4 \qquad (1)$$

where b_1, b_2, b_3, b_4 are the weight coefficients of each indicator variable x_1, x_2, x_3, x_4, and $b_1 + b_2 + b_3 + b_4 = 1$.

b) Transfer rate parameter α

The planning path shall pass through the high cycling demand, available land use section, and safe and low hazard place. Based on the Moore neighbourhood model with a radius of 1 metre, find an eligible cell $(w_{ij}(x,y) \geq 1)$ from the 8 surrounding neighbourhoods. The transfer rate is given by:

$$\alpha = \begin{cases} 0, & \text{the number of eligible cells} > \eta_1 \\ \beta_1, & \eta_2 < \text{the number of eligible cells} < \eta_1 \\ \beta_2, & \text{the number of eligible cells} < \eta_2 \end{cases} \qquad (2)$$

where β_1 and β_2 are the piecewise function value of α, $0 < \beta_2 < \beta_1$; η_1 and η_2 are the threshold value, $0 \leq \eta_2 \leq \eta_1 \leq 8$.

c) Transfer probability $P_{ij}(x,y)$

The transfer probability is calculated from:

$$P_{ij}(x,y) = \frac{(e^{\gamma})^{\lambda}}{1+e^{\left[-\alpha * w_{ij}(x,y)\right]}} \tag{3}$$

where γ and λ are random value in a range of values from 0 to 1, where λ is a control parameter. During each iteration, $P_{ij}(x,y)$ shall be compared with the threshold value δ; if $P_{ij}(x,y) > \delta$, the cell $c_{ij}(x,y)$ shall be on the planning path (bikeway).

4.3 Path generation

An improved CA path planning method is developed to determine the final bikeway through avoiding unsuitable cells in the network. All the unsuitable cells are obstacles that cannot be selected, while suitable cells obtained based on cell transfer rule shall be the optional cell in the algorithm. Traditional CA method starts from the origin node and proceeds to the destination node following the designed transition rules, which leads to easy-to-premature convergence. An improved CA method shall focus on filling in dead-end path in the whole bikeway network. Docking stations shall be the origin and destination nodes in the improved CA method. Detailed steps are listed as follows:

Step 1: Initialisation.

Set the status value for the optional cells as 0, for the obstacle cells as χ; set origin node and destination nodes as O and D with status value η.

Step 2: Contraction.

If the Moore neighbour in the positive direction of central cell $c_{i,j}$ (neighbour on direction of north, south, east and west) has more than 2 non-origin and non-destination cells with status value equal to χ at time t, this cell c shall be an obstacle cell at the time t+1 as follows:

$$\Psi_c^{t+1} = \begin{cases} \chi, K_t > 2, c \neq \eta \\ 0, K_t \leq 2, c \neq \eta \\ \eta, c = \eta \end{cases} \tag{4}$$

where $\Psi_{c_{i,j}}^{t+1}$ is the status value of central cell $c_{i,j}$ at time t+1; K_t is the cell number of Moore neighbour in the positive direction whose status value is χ.

Moreover, if the optional central cell c is located in the angle among four continuous obstacle neighbour cells, and neighbour cell against this angle is an optional cell, this cell c shall be an obstacle cell at the time t+1. Take upper left angle as an example, this rule can be expressed as follows:

$$\Psi_{c_{i,j}}^{t+1} = \chi, \quad if\ \Psi_{c_{i,j}}^{t} + \Psi_{c_{i+1,j+1}}^{t} = 0,\ and\ \Psi_{c_{i-1,j-1}}^{t} + \Psi_{c_{i-1,j}}^{t} + \Psi_{c_{i,j-1}}^{t} = 3\chi,\ and\ \Psi_{c_{i-1,j+1}}^{t} + \Psi_{c_{i+1,j-1}}^{t} > 0 \tag{5}$$

Step 3: Optimisation.

Many feasible paths may be obtained after Step 2 in the network. In order to select the only optimal path in the network, the host value is extended to calculate the path utility. The final path shall be the path with the maximum host value.

The overall planning framework is shown in Figure 2.

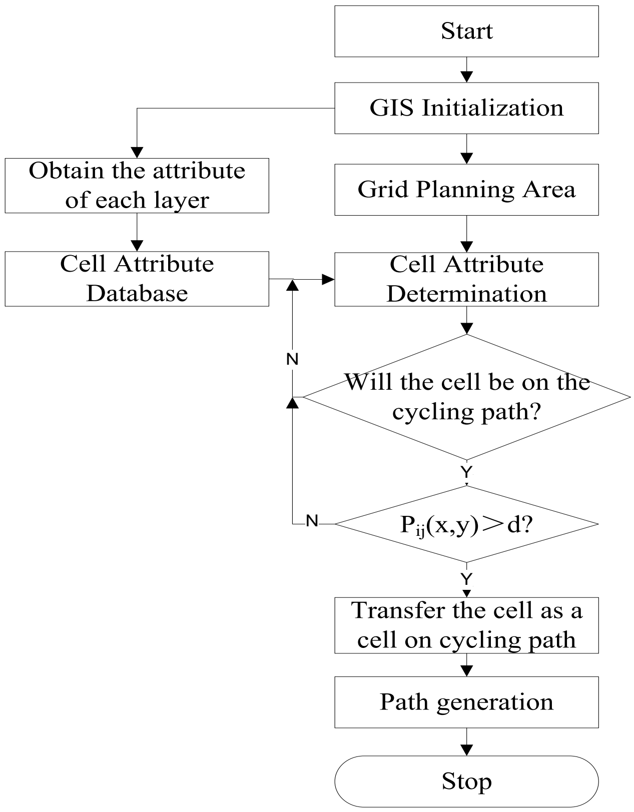


Figure 2 GIS-based CA bikeway planning framework

5 Application

5.1 Study area

In order to demonstrate the effectiveness of the proposed method, a real network (boundaries with expressways) located in the west of Singapore is selected as a study area as shown in Figure 3. Three Mass Rapid Transit (MRT) stations are located within this area, namely Lakeside, Chinese Garden and Jurong East. At present, there are footpaths with varying width alongside all roads linking most of the areas within the town centres, and there are no segregated bikeways.

After forecasting bike-sharing demand, 10 bike-sharing (docking) stations are determined as shown in Figure 3, where 3 docking stations are located nearby the 3 MRT stations, and the other 7 docking stations are located in the vicinity of residential or industrial buildings.

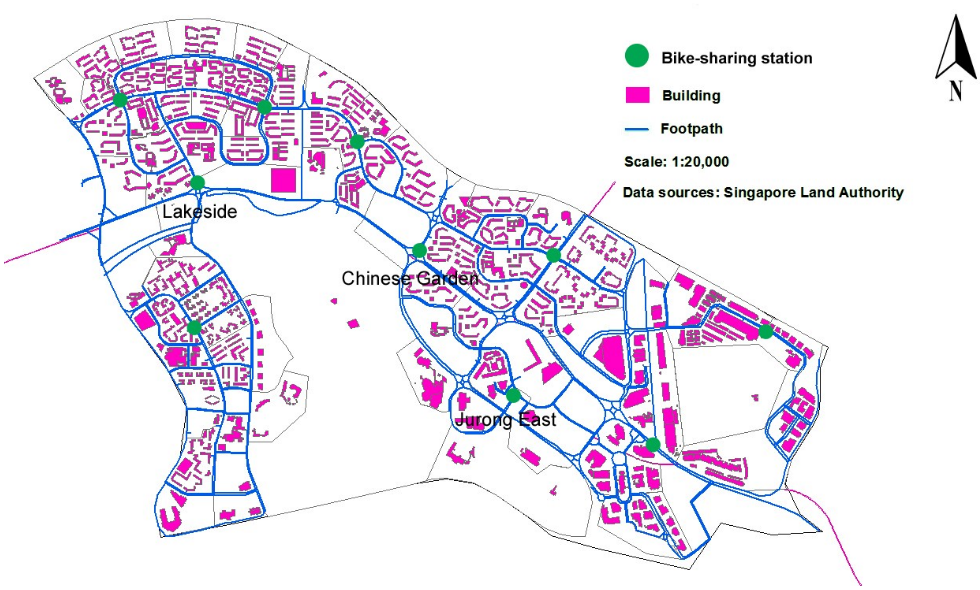


Figure 3 Map of study area

5.2 Data source

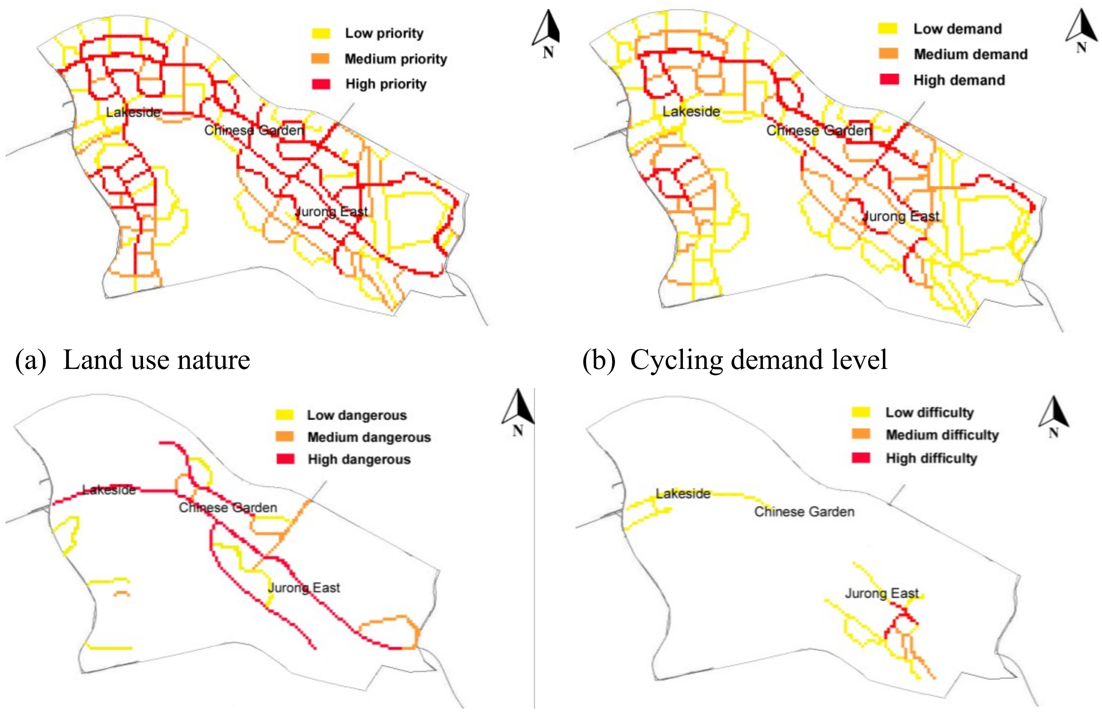
The data used in this analysis came from three sources. The first source is the home interview travel survey (HITS) which tends to under-report short-range non-motorised trips, hence a field transportation stated preference (SP) survey of non-motorised travellers was administered within the study area during three months from April 2014 to June 2014. Respondents were briefed about what is "bike-sharing" before answering the questions. The SP questions included likely usage frequency, trip purpose and destination, hazardous spot(s) along cycling route, preferred cycling parking location, how different conditions (weather, AM/PM peaks) affect respondent's decision to use bike-sharing, etc. Ultimately, the survey was completed by nearly 450 respondents. This survey served to predict the bike-sharing demand and also investigated potential unsafe or difficult to construct parthway segments.

The second source of data came from the Onemap [21], which is an integrated map system for government agencies. Three types of maps are considered in this study. One is the Urban Redevelopment Authority (URA) Master Plan 2019, which is the statutory land use plan over the next 10 to 15 years. Another is "street map" which contains roadside footpath, building and hydrology information. The other is geological map of Singapore, which is from Singapore Geology Office. These data provided the detailed GIS layers for determining the land use nature and construction difficulty.

The third source is the traffic accident database, which is from Singapore Police Force. The relevant cyclist and pedestrian collision data in study area was extracted to build the current safety level layer in this study.

5.3 Results

Once the data for all the indicators are prepared, they can be displayed on the grid cells. Based on land use planning and field observation, the first variable of land use nature can be valued as show in Figure 4a. The cycling demand is extracted from SP survey where the original zones of a cycling trip are distributed onto the nearest road segments as shown in Figure 4b. Traffic accident data are summed in Figure 4c. The terrain in the study area is relatively flat with firm solid ground. Construction technology is not difficult. Therefore, the variable value of construction difficulty in the study area is mostly related with construction cost, which was evaluated by field observation according to its social impact as shown in Figure 4d. The value of host variable $w_{ij}(x,y)$ for each cell can be calculated based on Eq. (1), where $b_1 = 0.4, b_2 = 0.4, b_3 = 0.1, b_4 = 0.1$. Set $\beta_1 = 5$, $\beta_2 = 0.5$, $\eta_1 = 6$, $\eta_2 = 3$, δ=0.5, and the suitable cells for path generation can be obtained based on cell transfer rule.



(a) Land use nature (b) Cycling demand level

(c) Traffic safety (d) Construction difficulty

Figure 4 Initial values of four indicator variables

After path generation process, the final planning bikeway paths for the study area are shown in Figure 5. In this map, all the bike-sharing stations are well connected within the planned bikeways. Combining the land use characteristics in Master Plan 2019, both the residential area and industry area are covered in Figure 5. The selected cells ensure that the planned bikeways with bike-sharing nodes can better supply the cycling demand with available land sources, as well as avoiding unsafe and difficult-to-construct area.

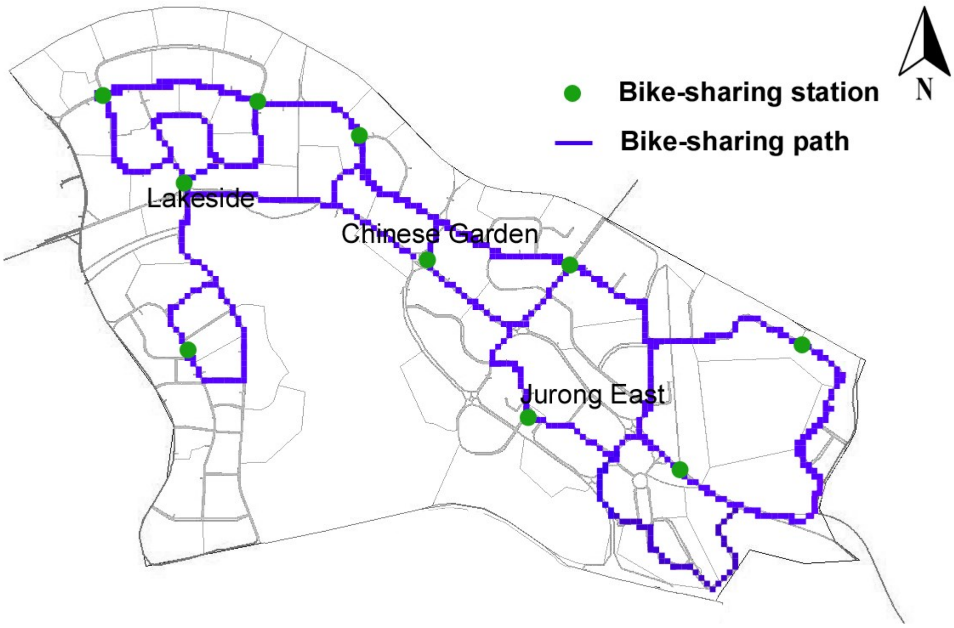


Figure 5 Final planning bike-sharing paths for study area

6 Conclusion

Singapore is aiming to be world's first "Smart Nation" by using hi-tech service in transport, eldercare and other public domains. This study proposed a CA bikeway planning model, fully operational in a GIS environment, to overcome the limitations of four-step approach for bikeway modelling. The model uses a 30×30 square metres grid cell mesh in the vector GIS data format with consideration of four indicator variables to determine the optional cells. An improved CA method is proposed with filling in dead-end path in the whole network, where non-optional cells are regarded as obstacle. Final bikeway network shall be obtained by connecting all the bike-sharing stations.

The contributions of the proposed method are threefold: (1) This proposed method can capture both the spatiotemporal behaviour, and the geospatial processing at the same time, which meets the demand and supply requirement in bikeway network planning; (2) The definition of the host variable in the CA model can be flexibly extended to other cases with combination of various influence factors. The paper has used Singapore as a case study to illustrate the application of the proposed method. This method can be applied in various countries and can incorporate localised factors, e.g. accessibility to other public transport services, competition from other first-/last-mile mobility services; (3) The algorithm can be repeated to map the priorities for the development of the cycling facilities. The final path is the output with the maximum host value. The threshold can be adjusted to generate the best k^{th} path.

However, the proposed method has the limitations of large size of cell setting. To ensure the computation performance on GIS platform, the cell size in CA model in this method is larger than the normal setting in other transportation scenario, e.g. intersection scenario, platform scenario. The definition can be adjusted in small-sized network to ensure an efficient calculation performance. Also, there is a minor gap between these two datasets (HIST and vehicle accident data) in temporal dimension. Considering the cycling network planning is a long-term project, the influence on the results can be neglected. The practicability of the proposed method has been verified by a study area in Singapore.

The techniques of determining the bikeway network with bike-sharing nodes serve as a useful tool to plan non-motorised transport facilities. It provides an idea of how to combine various influence factors into complex planning of bikeways on the GIS platform. Future study can focus on the design and implementation of sub modules, such as computer-aided survey module, historical data analysis module, and so on.

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